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Kimura et al.

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(54) **SEMICONDUCTOR LIGHT EMITTING DEVICE**

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This patent is subject to a terminal disclaimer.

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(63) Continuation of application No. 13/405,565, filed on Feb. 27, 2012, now Pat. No. 9,048,362.

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H01L 33/12 (2010.01)

H01L 33/06 (2010.01)

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CPC ***H01L 33/06*** (2013.01); ***B82Y 20/00*** (2013.01); ***H01L 33/12*** (2013.01); ***H01L 33/32*** (2013.01); *H01S 5/3408* (2013.01); *H01S 5/34333* (2013.01)

(58) **Field of Classification Search**

CPC H01L 33/04; H01L 33/06; H01L 33/32; H01L 33/002; H01L 33/007; H01L 33/0008; H01L 21/02507

See application file for complete search history.

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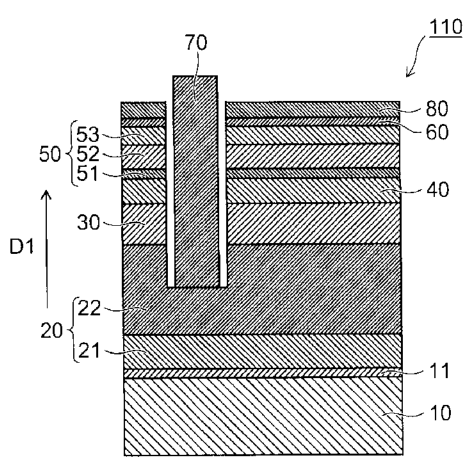
(57) **ABSTRACT**

According to one embodiment, a semiconductor light emitting device includes n-type and p-type semiconductor layers containing a nitride semiconductor and a light emitting layer. The emitting layer includes a barrier layer containing III group elements, and a well layer stacked with the barrier layer and containing III group elements. The barrier layer is divided into a first portion on an n-type semiconductor layer side and a second portion on a p-type semiconductor layer side, an In composition ratio in the III group elements of the second portion is lower than that of the first portion. The well layer is divided into a third portion on an n-type semiconductor layer side and a fourth portion on a p-type semiconductor layer side, an In composition ratio in the III group elements of the fourth portion is higher than that of the third portion.

18 Claims, 10 Drawing Sheets



(51) **Int. Cl.**

H01L 33/32	(2010.01)
B82Y 20/00	(2011.01)
H01S 5/343	(2006.01)
H01S 5/34	(2006.01)

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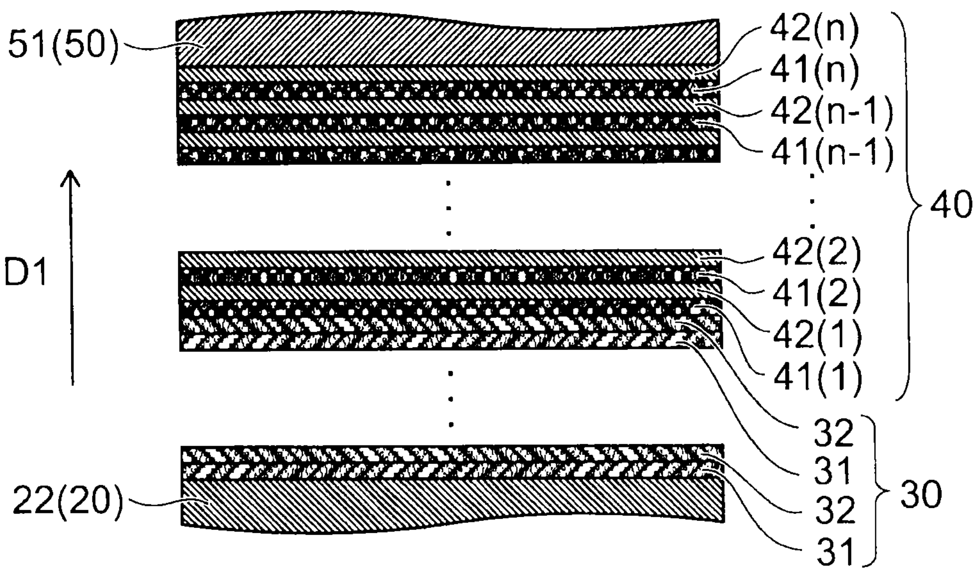
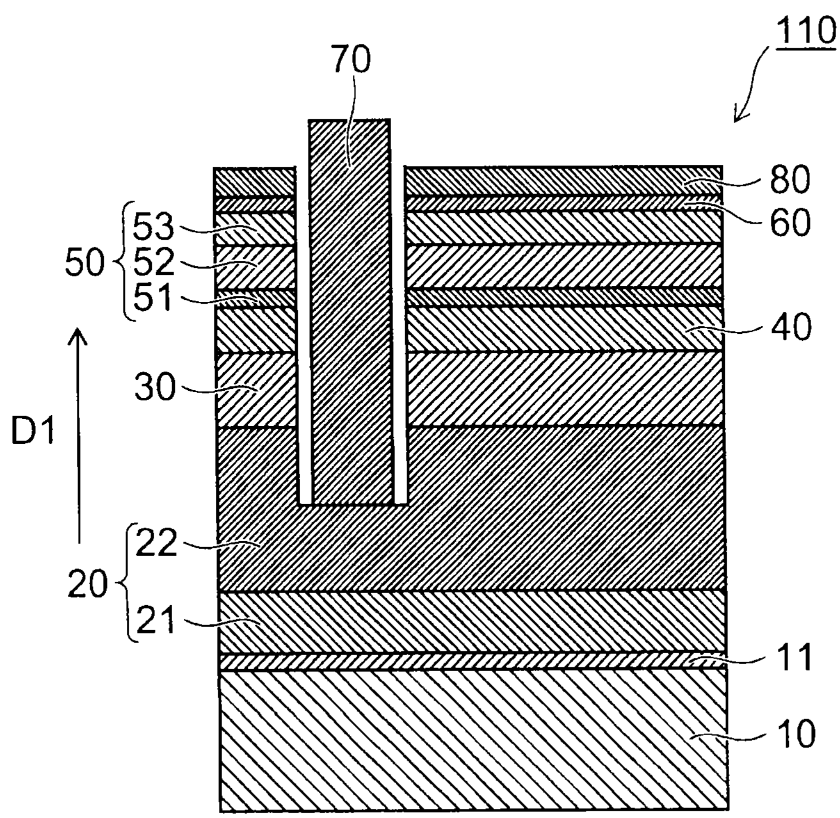

51(50)
42(n)
41(n)
42(n-1)
41(n-1)
40
D1
42(2)
41(2)
42(1)
41(1)
32
31
32
31
30
22(20)

FIG. 1


110
70
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53
52
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30
D1
22
20
21
11
10

FIG. 2

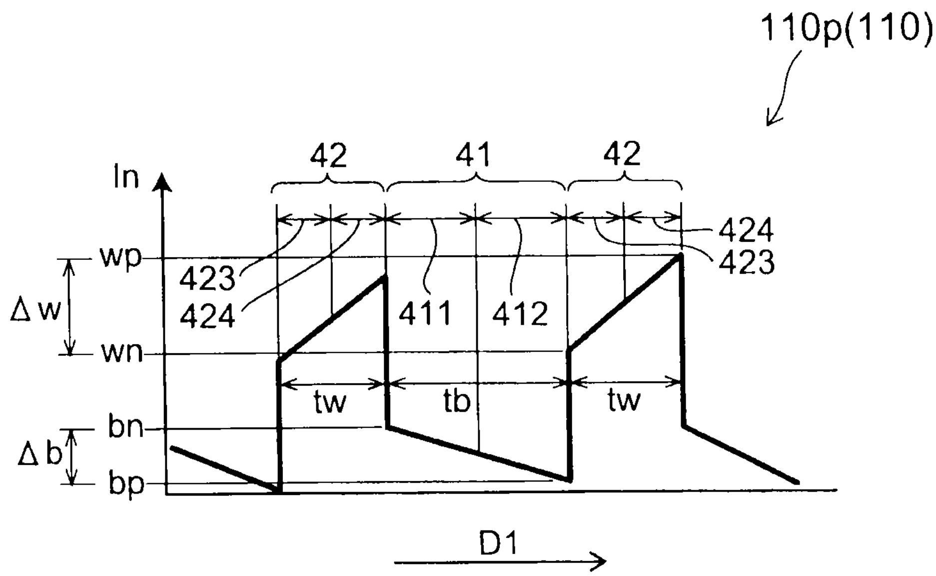

110p(110)
42
41
42
In
wp
wn
bn
bp
Δw
Δb
423
424
411
412
424
423
tw
tb
tw
D1

FIG. 3A

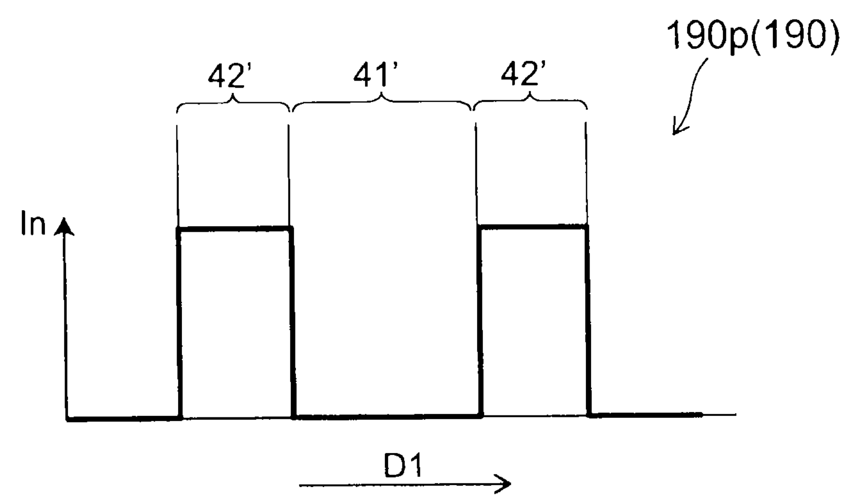

190p(190)
42'
41'
42'
In
D1

FIG. 3B

FIG. 4A

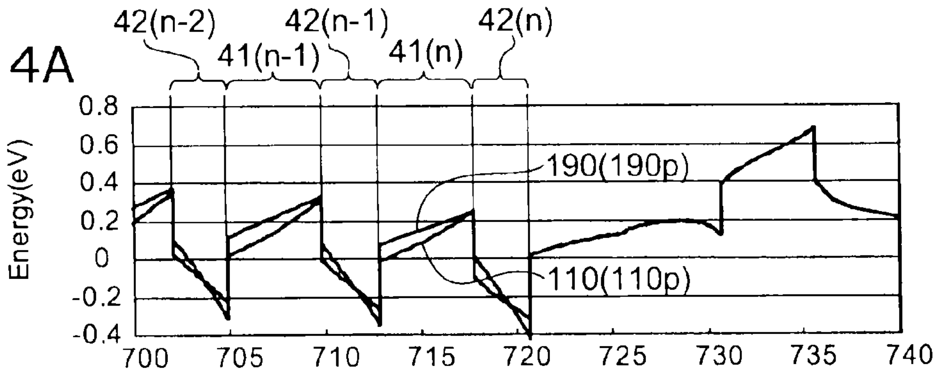


FIG. 4B

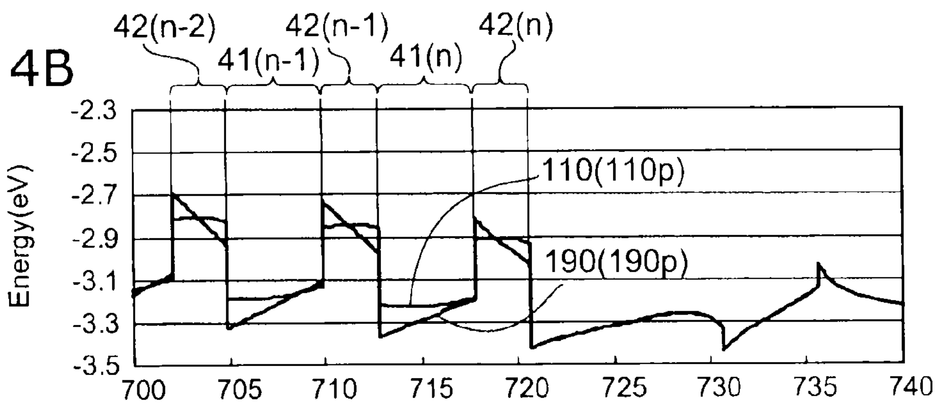


FIG. 4C

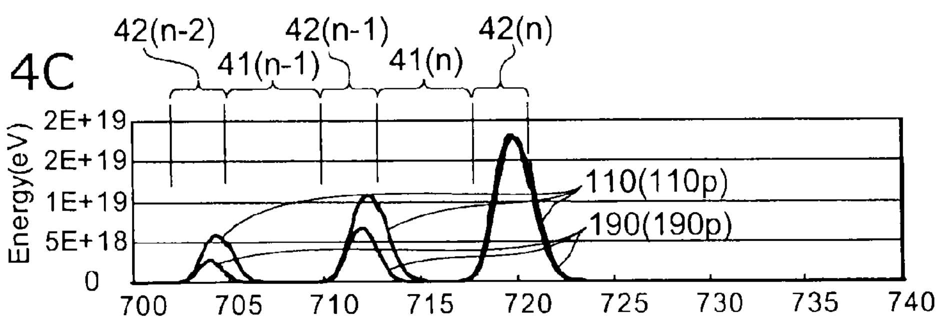


FIG. 4D

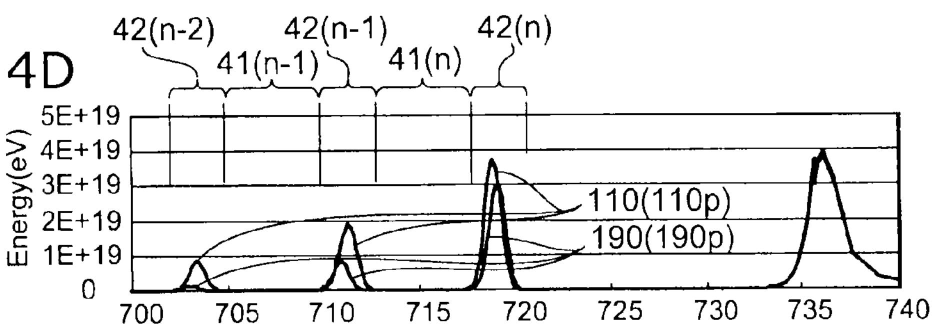


FIG. 5

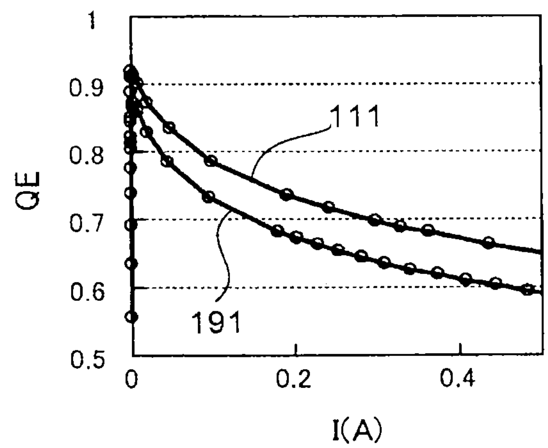


FIG. 6A

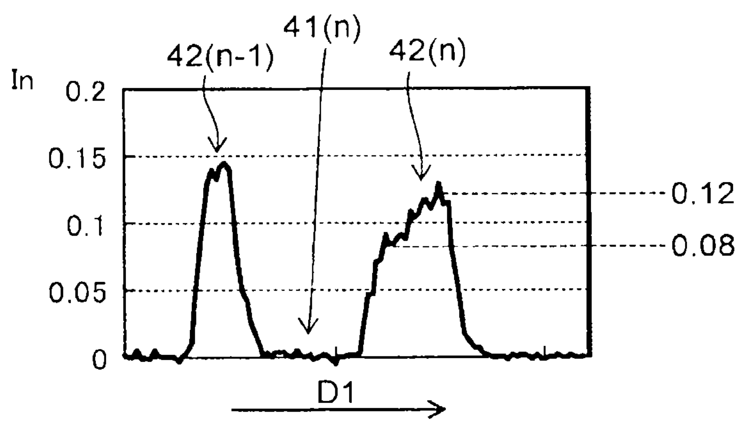


FIG. 6B

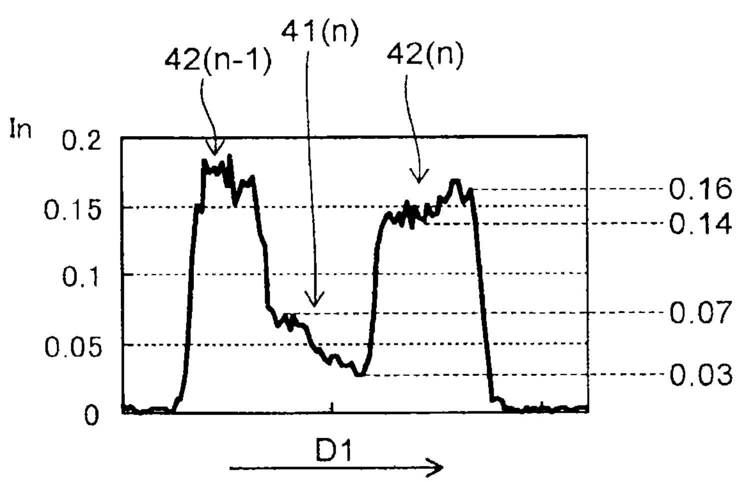


FIG. 7A

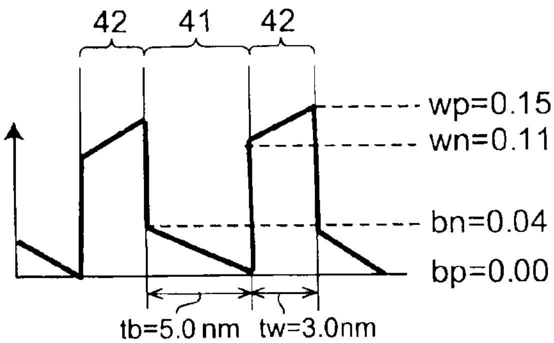


FIG. 7B

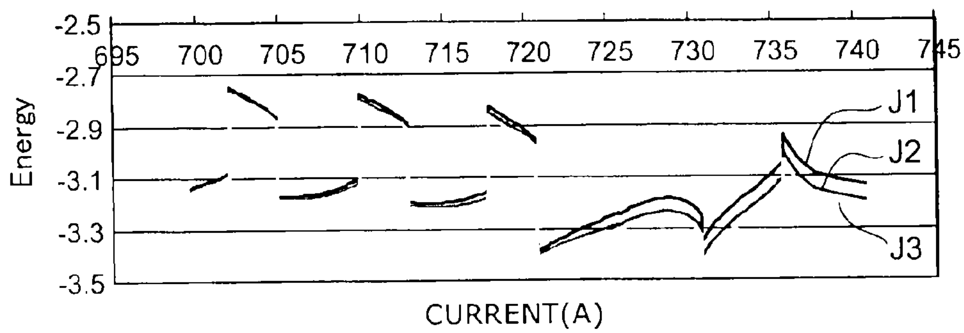


FIG. 8A

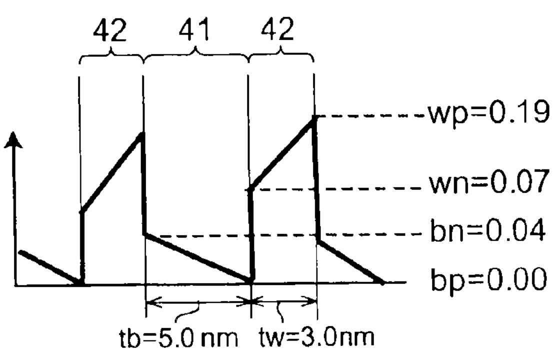


FIG. 8B

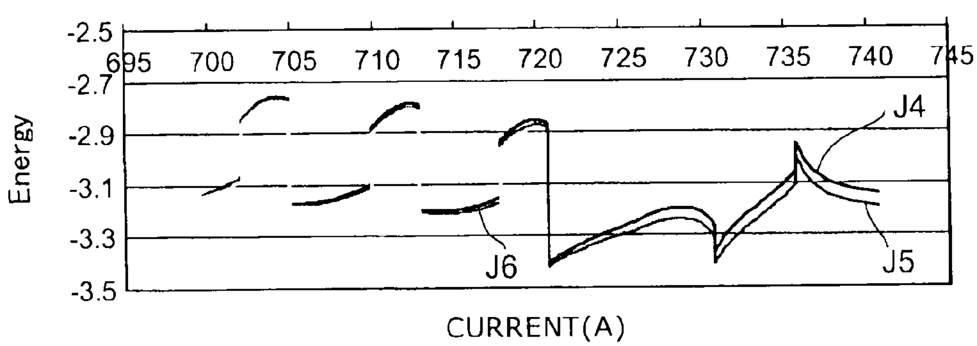


FIG. 9A

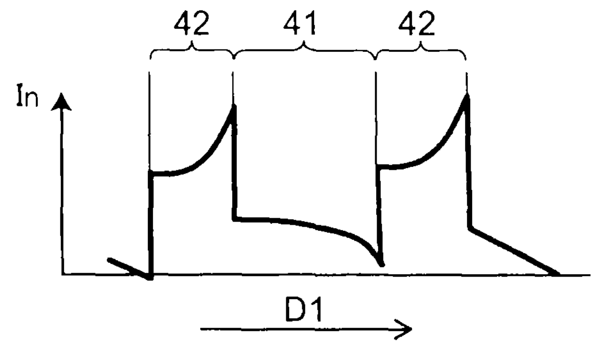


FIG. 9B

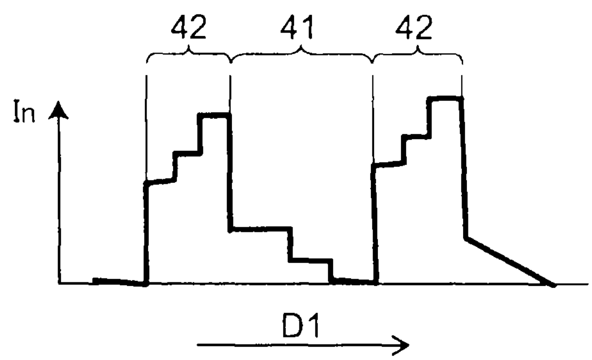


FIG. 9C

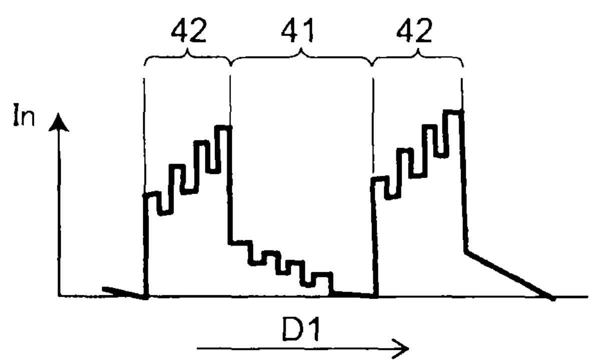


FIG. 9D

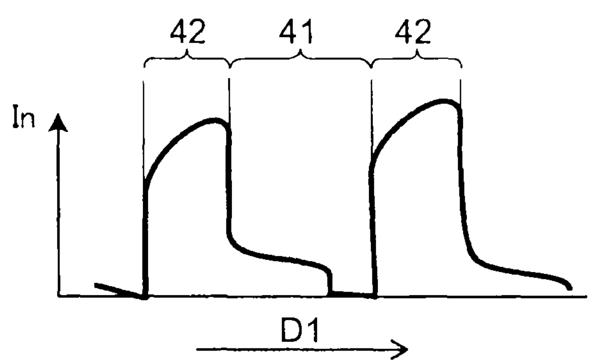


FIG. 10A

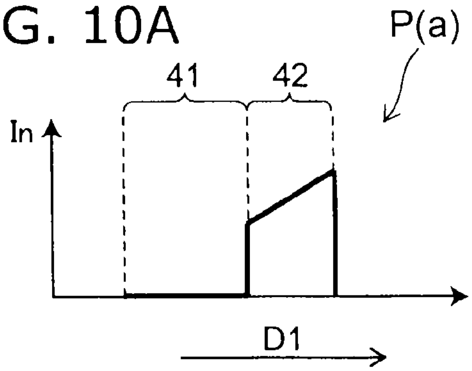


FIG. 10E

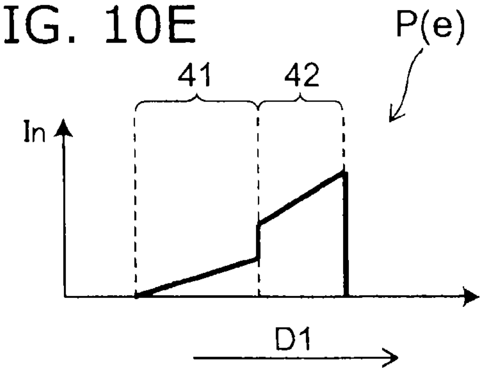


FIG. 10B

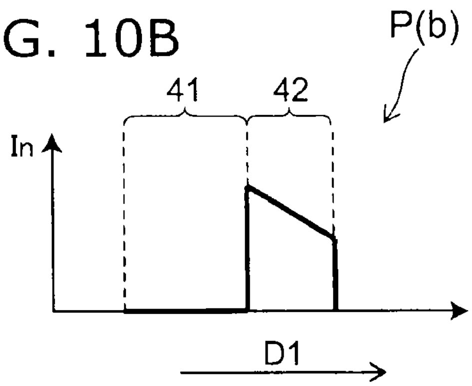


FIG. 10F

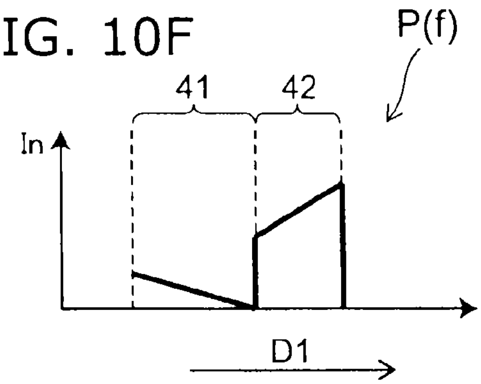


FIG. 10C

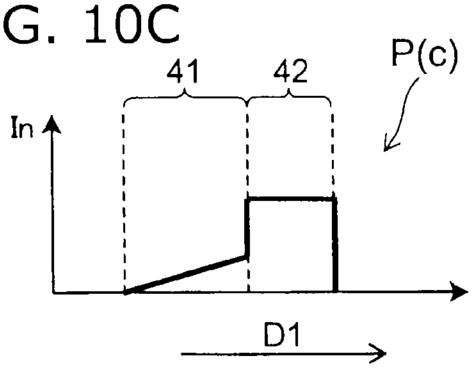


FIG. 10G

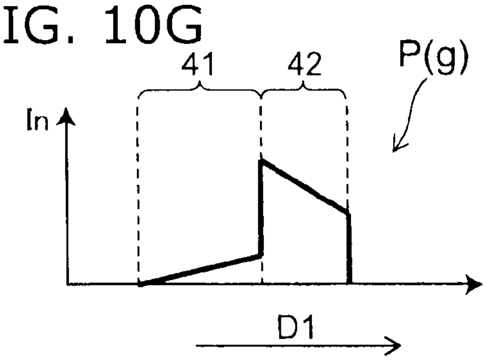


FIG. 10D

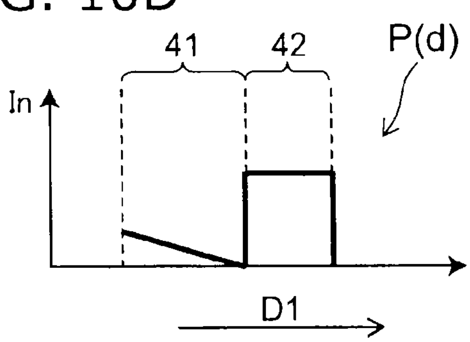
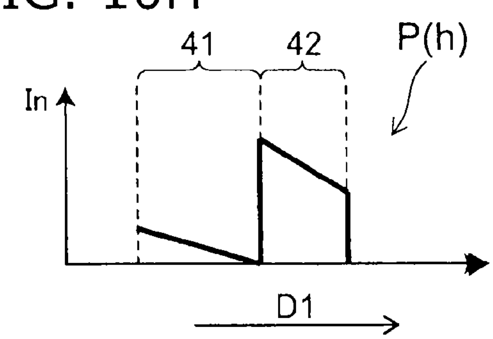


FIG. 10H



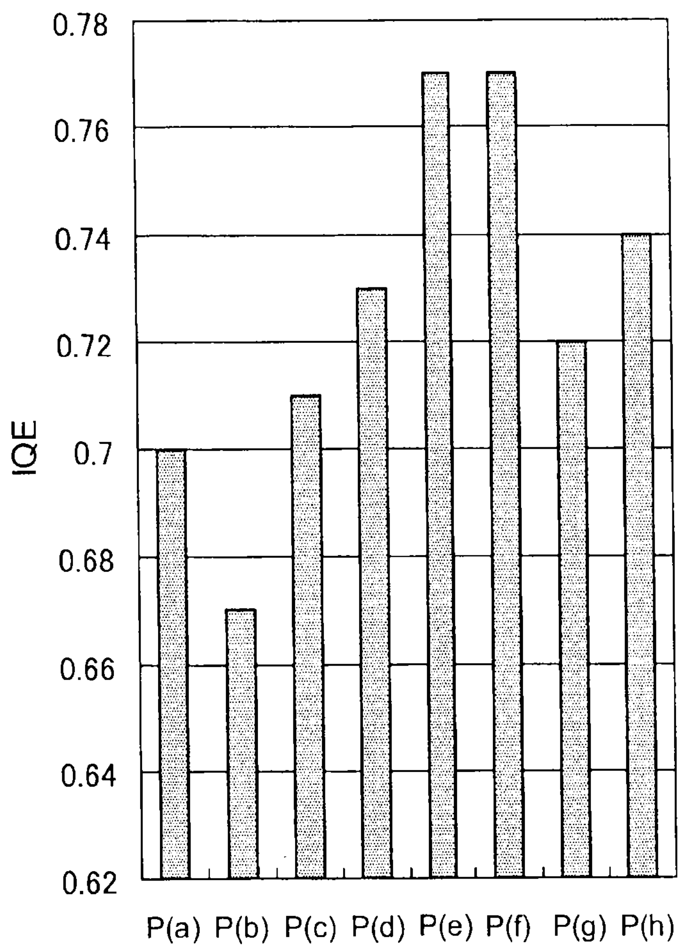


FIG. 11

FIG. 12A

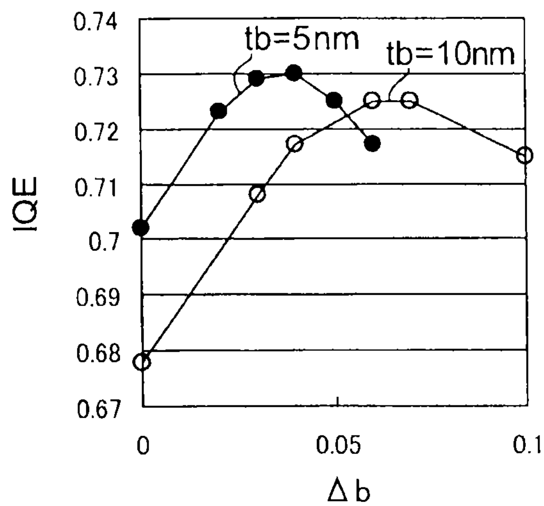


FIG. 12B

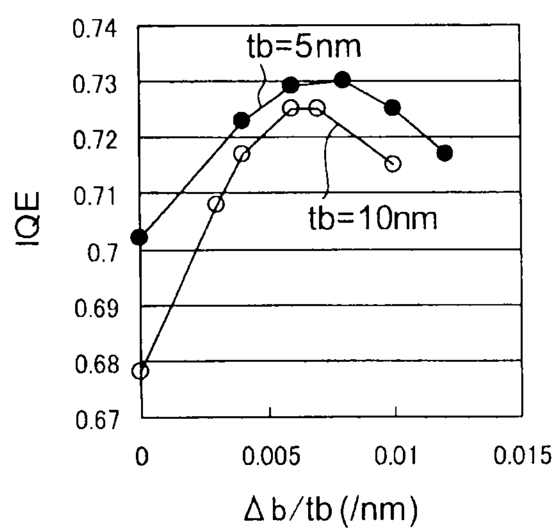


FIG. 13A

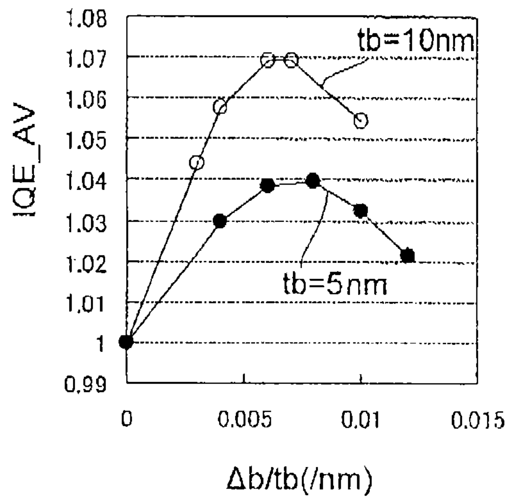
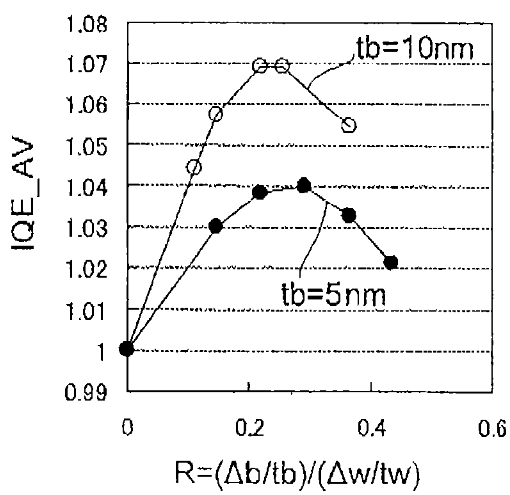


FIG. 13B



SEMICONDUCTOR LIGHT EMITTING DEVICE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. application Ser. No. 13/405,565, filed Feb. 27, 2012, which claims the benefit of priority from the prior Japanese Patent Application No. 2011-224365, filed on Oct. 11, 2011, the entire contents of each of which are incorporated herein by reference.

FIELD

Embodiments described herein relate generally to a semiconductor light emitting device.

BACKGROUND

Nitride-based III-V group compound semiconductors such as gallium nitride (GaN) are applied to a high-intensity light emitting diode (LED), a laser diode (LD), and the like, by taking advantage of their features of a wide band gap.

Each of these light emitting devices includes: an n-type semiconductor layer; a p-type semiconductor layer; and a light emitting layer provided between them and having a quantum well layer and a barrier layer.

Such semiconductor light emitting devices are being required to realize a high light emission efficiency.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic cross-sectional view illustrating the configuration of a part of a semiconductor light emitting device according to an embodiment;

FIG. **2** is a schematic cross-sectional view illustrating the configuration of the semiconductor light emitting device according to the embodiment;

FIGS. **3**A and **3**B illustrate profiles of In composition ratios of the light emitting layer;

FIGS. **4**A to **4**D illustrate energy bands and carrier concentration distributions;

FIG. **5** illustrates examination results regarding the semiconductor light emitting devices;

FIGS. **6**A and **6**B show In composition ratios;

FIG. **7**A to FIG. **8**B show In composition ratios and energy bands;

FIGS. **9**A to **9**D are schematic views illustrating other In composition ratios;

FIGS. **10**A to **10**H are schematic views showing an example of inclination of In composition ratios;

FIG. **11** illustrates internal quantum efficiencies; and

FIG. **12**A to FIG. **13**B illustrate the internal quantum efficiency.

DETAILED DESCRIPTION

According to one embodiment, a semiconductor light emitting device includes an n-type semiconductor layer containing a nitride semiconductor, a p-type semiconductor layer containing a nitride semiconductor and a light emitting layer provided between the n-type semiconductor layer and the p-type semiconductor layer. The light emitting layer includes a barrier layer containing III group elements, and a well layer stacked with the barrier layer in a direction going from the n-type semiconductor layer toward the p-type semiconductor layer and containing III group elements.

The barrier layer is divided into a first portion on a side of the n-type semiconductor layer and a second portion on a side of the p-type semiconductor layer. When at least the first portion contains In, an In composition ratio in the III group elements of the second portion is lower than an In composition ratio in the III group elements of the first portion.

The well layer is divided into a third portion on a side of the n-type semiconductor layer and a fourth portion on a side of the p-type semiconductor layer. When at least the fourth portion contains In, an In composition ratio in the III group elements of the fourth portion is higher than an In composition ratio in the III group elements of the third portion.

Various embodiments of the invention will be described hereinafter with reference to the accompanying drawings.

The drawings are schematic or conceptual; and the relationships between the thicknesses and widths of portions, the proportions of sizes among portions, etc., are not necessarily the same as the actual values thereof. Further, the dimensions and the proportions may be illustrated differently among the drawings, even for identical portions.

In the specification and the drawings of the application, components similar to those described in regard to a drawing thereinabove are marked with like reference numerals, and a detailed description is omitted as appropriate.

(Embodiments)

FIG. **1** is a schematic cross-sectional view illustrating a part of a configuration of a semiconductor light emitting device according to an embodiment.

FIG. **2** is a schematic cross-sectional view illustrating the configuration of the semiconductor light emitting device according to the embodiment.

As shown in FIG. **2**, the semiconductor light emitting device **110** according to the embodiment includes: an n-type semiconductor layer **20**; a p-type semiconductor layer **50**; and a light emitting layer **40** provided between the n-type semiconductor layer **20** and the p-type semiconductor layer **50**. In the semiconductor light emitting device **110**, a stacked body **30** may be provided between the light emitting layer **40** and the n-type semiconductor layer **20**.

Each of the n-type semiconductor layer **20** and the p-type semiconductor layer **50** contains a nitride semiconductor.

The light emitting layer **40** is, for example, an active layer. The stacked body **30** is, for example, a super-lattice layer.

In the semiconductor light emitting device **110**, the buffer layer **11** is provided on a major surface (for example, c-plane) of a substrate **10** composed of, for example, sapphire, and, for example, an undoped-GaN foundation layer **21** and an n-type GaN contact layer **22** are provided thereon. The n-type GaN contact layer **22** is contained in the n-type semiconductor layer **20**. The GaN foundation layer **21** may also be contained in the n-type semiconductor layer **20** for convenience.

A stacked body **30** is provided on the n-type GaN contact layer **22**. In the stacked body **30**, for example, first crystal layers **31** and second crystal layers **32** are stacked alternatively.

On the stacked body **30**, the light emitting layer **40** (active layer) is provided. The light emitting layer **40** has, for example, a multiple quantum well (MQW) structure. That is, the light emitting layer **40** includes the structure in which a plurality of barrier layers **41** and a plurality of well layers **42** are stacked alternatively and repeatedly. The detailed configuration of the barrier layer **41** and the well layer **42** will be described later.

On the light emitting layer **40**, a p-type AlGaN layer **51**, a Mg doped GaN layer **52**, and a p-type GaN contact layer **53**, are provided in this order. The p-type AlGaN layer **51** has a function as an electron overflow suppression layer. The p-type AlGaN layer **51**, the Mg doped GaN layer **52**, and the p-type GaN contact layer **53**, are contained in the p-type semiconductor layer **50**. Furthermore, a transparent electrode **60** is provided on the p-type GaN contact layer **53**.

Then, an n-side electrode **70** is provided on the n-type GaN contact layer **22** by removing a part of the n-type GaN contact layer **22**, which is the n-type semiconductor layer **20**, and areas of the stacked body **30**, the light emitting layer **40**, and the p-type semiconductor layer **50**, which correspond to the part. A stacked structure of, for example, Ti/Pt/Au is used for the n-side electrode **70**, for example. In contrast, a p-side electrode **80** is provided on the transparent electrode **60**.

As described above, the semiconductor light emitting device **110** of the specific example according to the embodiment is a light emitting diode (LED).

The semiconductor light emitting device **110** can be manufactured, for example, as follows.

First, the substrate **10** of, for example, a c-plane sapphire subjected to organic cleaning or acid cleaning, is introduced into a reactor of MOCVD (Metal Organic Chemical Vapor Deposition) apparatus, and is heated to about 1100° C. on a susceptor in the reactor. Thereby, the oxide film of the surface of the substrate **10** is removed.

Next, the buffer layer **11** is grown on the major surface (c-plane) of the substrate **10** at a thickness of 30 nm. Furthermore, an undoped GaN foundation layer **21** of is grown on the buffer layer **11** at a thickness of 3 micrometers (μm). Moreover, an n-type GaN contact layer **22** composed of Si doped GaN is grown on the GaN foundation layer **21** at a thickness of 2 μm.

Next, on the n-type GaN contact layer **22**, the stacked body **30** is formed by stacking the first crystal layers **31** composed of $In_xGa_{1-x}N$, and second crystal layers **32** composed of $In_yGa_{1-y}N$, alternatively by 30 periods.

Next, the barrier layers **41** and the well layers **42** are alternatively stacked on the stacked body **30**.

Furthermore, a 5 nm thick AlGaN layer having Al composition ratio of 0.003 is grown on the top barrier layer **41**, and subsequently, a 10 nm thick Mg doped AlGaN layer **51** having Al composition ratio of 0.1, a 80 nm thick Mg doped p-type GaN layer **52** (Mg concentration is $2\times10^{19}/cm^3$), and an about 10 nm thick high concentration Mg doped GaN layer **53** (Mg concentration is $1\times10^{21}/cm^3$), are stacked thereon. Then, the substrate on which the above-mentioned crystals are grown is taken out from the reactor of MOCVD apparatus.

Next, a part the multilayered film structure is exposed by subjecting the n-type GaN contact layer **22** to dry etching to the middle, and the n-side electrode **70** of Ti/Pt/Au is formed thereon. Furthermore, the transparent electrode **60** composed of ITO (Indium Tin Oxide) is formed on the surface of the high concentration Mg doped GaN layer **53**, and the p-side electrode **80** composed of Ni/Au with diameter of, for example, 80 μm is formed in a part of the transparent electrode **60**. Thereby, the semiconductor light emitting device **110** is fabricated.

Although, the example using MOCVD (metalorganic chemical vapor deposition) method as a film formation method have been described above, another method, such as for example, a molecular beam epitaxial (MBE) method or a halide vapor phase epitaxial (HVPE) method, is also applicable.

Next, the multiple quantum well structure of the light emitting layer **40** will be described.

As shown in FIG. **1**, the multi quantum wells structure of the light emitting layer **40** has a plurality of barrier layers **41** (**1**) to **41** (*n*) and a plurality of well layers **42** (**1**) to **42** (*n*). In addition, "n" contained in reference numerals is an integer not less than 2, corresponding to the number of the layer.

In the specification, when the plurality of barrier layers **41** (**1**) to **41** (*n*) and the plurality of well layers **42** (**1**) to **42** (*n*) are referred to without being distinguished, they are referred to as the barrier layers **41** and the well layers **42**, respectively.

The plurality of barrier layers **41** have the first barrier layer **41**(**1**), the second barrier layer **41**(**2**), - - , the (n−1)-th barrier layer **41**(*n*−1), and the n-th barrier layer **41**(*n*) from the n-type semiconductor layer **20** towards the p-type semiconductor layer **50**.

The plurality of well layers **42** have the first well layer **42**(**1**), the second well layer **42**(**2**), - - , the (n−1)-th well layer **42**(*n*−1), and the n-th well layer **42**(*n*) from the n-type semiconductor layer **20** toward the p-type semiconductor layer **50**.

Each of the barrier layer **41** and the well layer **42** contains III group elements. Small amounts of Al or the like may be contained therein.

An nitride semiconductor containing, for example, In, is used for the well layer **42**. The band gap energy of the barrier layer **41** is larger than the band gap energy of the well layer **42**.

For example, the barrier layer **41** contains $In_bGa_{1-b}N$ ($b\geq0$). The thickness of the barrier layer **41** is represented as t_b (nanometers). The thickness t_b of the barrier layer **41** is, for example, not more than 10 nanometers (nm).

The well layer **42** contains $In_wGa_{1-w}N$ ($0<w<1$). The thickness of the well layer **42** is represented as t_w (nanometers). The thickness t_w of the well layer **42** is, for example, not less than 2.5 nm and not more than 6 nm.

Here, the band gap of the well layer **42** is lower than the band gap of the barrier layer **41**. This is equivalent to $b<w$, for a case of, for example, a system using $In_bGa_{1-b}N$ as the barrier layer **41** and $In_wGa_{1-w}N$ as the well layer **42**.

FIGS. **3**A and **3**B illustrate profiles of In composition ratios of the light emitting layer.

In FIGS. **3**A and **3**B, the horizontal axis represents the position of the light emitting layer **40** (position in the thickness direction) and the vertical axis represents In composition ratio.

In FIG. **3**A, a part of the profile **110**P of In composition ratio in the light emitting layer of the semiconductor light emitting device **110** according to the embodiment is shown.

In FIG. **3**B, a part of the profile **190**P of In composition ratio in a light emitting layer of a semiconductor light emitting device **190** according to a reference example is shown.

In both of the drawings, for the sake of simple explanation, In composition ratios of two well layers **42** and one barrier layer **41** provided between these two well layers **42** are represented.

As represented in FIG. **3**A, in the profile **110**P of In composition of the semiconductor light emitting device **110** according to the embodiment, In composition ratio in the III group elements of the barrier layer **41** decreases in a direction going from the n-type semiconductor layer **20** toward the p-type semiconductor layer **50** (first direction D**1**), and In composition ratio in the III group elements of the well layer **42** increases in the first direction D**1**.

That is, when one barrier layer **41** is divided into a first portion **411** on the side of the n-type semiconductor layer **20** and a second portion **412** on the side of the p-type semiconductor layer **50**, In composition ratio averaged by the thickness of the second portion **412** is lower than In composition ratio averaged by the thickness of the first portion **411**.

Here, In composition ratio averaged by the thickness of a layer is set to average In composition ratio.

If In composition ratio in the III group elements of the barrier layer **41** decreases toward the first direction D**1**, the band gap of the barrier layer **41** becomes smaller as the barrier layer **41** is closer to the n-type semiconductor layer **20**, and the gap becomes larger as the barrier layer **41** is closer to the p-type semiconductor layer **50**. That is, the band gap in one barrier layer **41** becomes larger gradually toward the first direction D**1**.

In contrast, when one well layer **42** is divided into a third portion **423** on the side of the n-type semiconductor layer **20** and a fourth portion **424** on the side of the p-type semiconductor layer **50**, average In composition ratio of the fourth portion **424** is lower than average In composition ratio of the third portion **423**.

If In composition ratio in the III group elements of the well layer **42** increases in the first direction D**1**, the band gap of the well layer **42** becomes larger as the well layer **42** is closer to the n-type semiconductor layer **20**, and the gap becomes smaller as the well layer **42** is closer to the p-type semiconductor layer **50**. That is, the band gap in one well layer **42** becomes smaller gradually toward the first direction D**1**.

In order to change the band gap gradually, for a case of, for example, a system using $In_bGa_{1-b}N$ as the barrier layer **41** and $In_wGa_{1-w}N$ as the well layer **42**, In composition ratio b of the barrier layer **41** may be gradually made smaller toward the first direction D**1** and In composition ratio w of the well layer **42** may be gradually made larger toward the first direction D**1**.

As described above, the band structure in the light emitting layer **40** is modulated by decreasing In composition ratio in the III group elements of the barrier layer **41** toward the first direction D**1** and increasing In composition ratio in the III group elements of the well layer **42** toward the first direction D**1** to thereby optimize the band structure when a voltage is applied to the light emitting layer **40**. This suppresses decline in the recombination probability of electrons and holes or the efficiency of carrier injection, thereby achieving improvement in light emission efficiency.

In the profile **190**P of In composition ratio of the semiconductor light emitting device **190** according to the reference example shown in FIG. **3**B, In composition ratios toward the first direction D**1** are constant for both of the barrier layer **41'** and the well layer **42'**.

Here, in a quantum well layer composed of a nitride semiconductor having a wurtzite structure grown in the c-axis direction, the internal electric field generated in the layer degrades the light emission recombination and the efficiency of carrier injection of a light emitting device such as LED. This is due to generation of a piezo-electric field by lattice strain derived from mismatch between the lattice constant of the crystal (for example, InGaN) constituting the well layers **42** and **42'**, and the lattice constant of the crystal (for example, InGaN with In composition ratio different from In composition ratio of the well layer **42'**) constituting the barrier layers **41** and **41'**. If the band structure of the light emitting layer **40** is modulated by the piezo-electric field, the recombination probability of electrons and holes and the efficiency of carrier injection are degraded.

In the semiconductor light emitting device **190** according to the reference example, the light emission efficiency is degraded due to the modulation of the band structure by the piezo-electric field.

In contrast, in the semiconductor light emitting device **110** according to the embodiment, as shown in FIG. **3**A, by changing In composition ratios of the barrier layer **41** and the well layer **42** in the first direction D**1**, the band structure when an electric field is applied to the light emitting layer **40** is optimized so that the recombination probability of electrons and holes and the efficiency of carrier injection are enhanced.

In addition, in the MQW structure where a plurality of barrier layers **41** and a plurality of well layers **42** are provided, the profile as shown in FIG. **3**A, in which In composition ratio of the barrier layer **41** decreases toward the first direction D**1**, and the In composition ratio of the well layer **42** increases toward the first direction D**1**, may be applied to all of the plurality of barrier layers **41** and the plurality of well layers **42**, or may be applied to a part of the barrier layers **41** and a part of the well layers **42**.

Next, a specific example of the barrier layer **41** and the well layer **42** of the semiconductor light emitting device **110** according to the embodiment will be described.

In addition, although the light emitting layer **40** has a plurality of barrier layers **41** and a plurality of well layers **42**, for the sake of simple explanation, description will be done for a case in which average In composition ratios in each of the plurality of barrier layers **41** are mutually the same and thicknesses in each of the plurality of barrier layers **41** are also mutually the same. Furthermore, similarly, description will be done for a case in which average In composition ratios in each of the plurality of well layers **42** are mutually the same and thicknesses in each of the plurality of well layers **42** are also mutually the same.

In the semiconductor light emitting device **110** according to the specific example, thickness t_b of the barrier layer **41** is made thin being not more than 10 nm. By this procedure, holes injected from the p-type semiconductor layer **50** are efficiently supplied to the light emitting layer **40**, thereby, enhancing the light emission efficiency of the semiconductor light emitting device **110**. Furthermore, the operating voltage of the semiconductor light emitting device **110** is reduced to a practically demanded level.

In the semiconductor light emitting device **110** according to the embodiment, it is desirable that the thickness t_w of the well layer **42** is as thick as possible, preferably, not less than 3 nm, more preferably, not less than 4 nm.

In the semiconductor light emitting device **110** according to the embodiment, when In composition ratio at the interface of one barrier layer **41** on the side of the n-type semiconductor layer **20** is defined as bn, and the In composition ratio at the interface of the barrier layer **41** on the side of the p-type semiconductor layer **50** is defined as bp, it is preferable to make bn not less than 0.02, more preferably about 0.04.

In one barrier layer **41**, this In composition ratio b is gradually decreased toward the first direction D**1**. It is desirable to make In composition ratio bp at the interface of the barrier layer **41** on the side of the p-type semiconductor layer **50** to 0.00. As In composition ratio bp becomes smaller, improvement in light emission efficiency is achieved without degrading the crystallinity of the barrier layer **41**. Here, 0.00 of the In composition ratio bp includes the case where In is unintentionally contained in a manufacturing process.

Moreover, it is preferable to make the absolute value (Δb) of the difference between In composition ratio bn and In composition ratio bp, for example, larger than 0.02 and smaller than 0.06, more preferably about 0.04.

In the semiconductor light emitting device **110** according to the embodiment, when In composition ratio at the interface of one well layer **42** (for example, the well layer **42** neighboring the barrier layer **41** on the side of the p-type semiconductor layer **50**) on the side of the n-type semiconductor layer **20** is defined as wn, and In composition ratio at the interface of the well layer **42** on the side of the p-type semiconductor layer **50** is defined as wp, if the device **110** is LED that emits blue light, it is preferable to make In composition ratio wn not more than 0.10, more preferably about 0.06.

This In composition ratio w is made to increase gradually toward the first direction **D1** in one well layer **42**. It is preferable to make In composition ratio wp at the interface of the well layer **42** on the side of the p-type semiconductor layer not less than 0.14, more preferably about 0.18. By modulating the composition ratio in such a manner, the light emission efficiency can be improved without degrading the crystallinity of the well layer **42**.

Furthermore, it is preferable to make the absolute value (Δw) of the difference between In composition ratio wn and In composition ratio wp, for example, larger than 0.04 and smaller than 0.12, more preferably not less than 0.06, further preferably about 0.10.

The configuration of complementary energy bands produced by gradual changes of the thickness of In composition ratio of the barrier layer **41** and gradual changes of the thickness of In composition ratio of the well layer **42** described above, realizes high light emission efficiency of the semiconductor light emitting device **110**.

FIGS. **4**A to **4**D illustrate energy bands and carrier concentration distributions.

In any of the drawings of FIGS. **4**A to **4**D, the horizontal axis represents a position (position in the thickness direction). The horizontal axes of FIGS. **4**A to **4**D show positions of a part including three well layers **42**(*n*), **42**(*n*−1) and **42**(*n*−2) on the side of the p-type semiconductor layer **50** and two barrier layers **41**(*n*) and **41**(*n*−1) among them.

FIG. **4**A shows the energy band diagram of a conduction band, FIG. **4**B shows the energy band diagram of a valence band, FIG. **4**C shows the concentration of electrons, and FIG. **4**D shows the concentration of holes.

In FIGS. **4**A to **4**D, cases of the profile **110**P of In composition ratio of the semiconductor light emitting device **110** according to the embodiment represented in FIG. **3**A and the profile **190**P of In composition ratio of the semiconductor light emitting device **190** according to the reference example represented in FIG. **3**B are illustrated, respectively.

In the profile **110**P of In composition ratio of the semiconductor light emitting device **110** according to the embodiment, for the well layer **42**, In composition ratio wn is 0.10 and In composition ratio wp is 0.18, i.e., Δw=0.08, and in the barrier layer **41**, In composition ratio by is 0.00 and In composition ratio bn is 0.04, i.e., Δb=0.04. In addition, the thickness t_w of the well layer **42** is 3 nm and the thickness t_b of the barrier layer **41** is 5 nm.

Furthermore, in the profile **190**P of In composition ratio of the semiconductor light emitting device **190** according to the reference example, In composition ratio w of the well layer **42'** is 0.13 and In composition ratio b of the barrier layer **41'** is 0.00. In addition, the thickness t_w of the well layer **42'** is 3 nm and the thickness t_b of the barrier layer **41** is 5 nm.

As shown in FIGS. **4**A and **4**B, if the profile **110**P of In composition according to the embodiment is applied, the energy band diagrams of the conduction band and the valence band change as compared with a case where the profile **190**P of In composition according to the reference example is applied.

Especially, significant change appears in the energy band diagram of the valence band represented in FIG. **4**B. By applying the profile **110**P of In composition according to the embodiment, modulation of the valence band in the light emitting layer **40** due to the internal electric field is suppressed. That is, the energy band diagram of the valence band becomes rectangular by the mutual increase and decrease in In composition ratios of the barrier layer **41** and the well layer **42**.

Thereby, as shown in FIG. **4**D, localization of holes at the interface between the well layer **42** and the barrier layer **41** is suppressed. Furthermore, spatial dissociation of electrons and holes is suppressed by the well layer **42** and the barrier layer **41**. Moreover, the efficiency of hole injection into the well layer **42** on the side of the n-type semiconductor layer **20** is increased. These results extremely enhances the efficiency of light emission of the semiconductor light emitting device **110** according to the embodiment in comparison with the efficiency of light emission of the semiconductor light emitting device **190** according to the reference example.

Hereinafter, results of examination acting as the base for finding out the conditions as mentioned above will be described.

In the examination, a semiconductor light emitting device is configured by changing the configuration of the light emitting layer **40** (the way for modulating the thickness or In composition ratio of the barrier layer **41** and the way for modulating the thickness or In composition ratio of the well layer **42**), and the internal quantum efficiencies for the respective cases are compared.

EXAMPLE

In an semiconductor light emitting device **111** according to the embodiment, the number of the barrier layers **41** and the well layers **42** is eight periods.

In the semiconductor light emitting device **111**, In composition ratio bn at the interface of the barrier layer **41** on the side of the n-type semiconductor layer **20** is 0.04, In composition ratio by at the interface of the barrier layer **41** on the side of the p-type semiconductor layer **50** is 0.00, and In composition ratio in the layer changes linearly.

Furthermore, in the semiconductor light emitting device **111**, In composition ratio wn at the interface of the well layer **42** on the side of the n-type semiconductor layer **20** is 0.08, In composition ratio wp at the interface of the well layer **42** on the side of the p-type semiconductor layer **50** is 0.18, and In composition ratio in the layer changes linearly.

Moreover, in a semiconductor light emitting device **191** according to the reference example, the number of barrier layers **41'** and well layers **42'** is eight periods. In the semiconductor light emitting device **191** according to the reference example, In composition ratio b of the barrier layer **41'** is constant at 0.00 in the layer (namely, the layer is composed of GaN), and In composition ratio w of the well layer **42'** is constant at 0.13 in the layer (namely, the layer is composed of $In_{0.13}Ga_{0.87}N$).

In any of the semiconductor light emitting devices **110** and **190**, the thickness t_b of the barrier layer **41** is a constant value of 5 nm, and the thickness t_w of the well layer **42** is a constant value of 3 nm.

FIG. **5** illustrates examination results regarding the semiconductor light emitting devices.

In FIG. **5**, the horizontal axis represents current I (ampere: A), and the vertical axis shows the internal quantum efficiency QE.

In FIG. **5**, the internal quantum efficiency of the semiconductor light emitting device **111** according to the embodiment and the internal quantum efficiency of the semiconductor light emitting device **191** according to the reference example are represented.

In addition, in FIG. **5**, the internal quantum efficiency is represented by relative values using the peak top value of the internal quantum efficiency of the semiconductor light emitting device **191** according to the reference example as 1.

As shown in FIG. **5**, it is understood that the internal quantum efficiency of the semiconductor light emitting device **111** according to the embodiment is clearly improved than the internal quantum efficiency of the semiconductor light emitting device **191** according to the reference example.

FIGS. **6**A and **6**B show one example of analysis results of In composition ratio using a three-dimensional atom probe, respectively.

In FIGS. **6**A and **6**B, the horizontal axis represents a position, and the vertical axis represents In composition ratio.

In FIGS. **6**A and **6**B, In composition ratios of the n-th well layer **42**(*n*), the n-th barrier layer **41**(*n*), and the (n−1)-th well layer **42**(*n*−1) are shown, respectively.

In FIG. **6**A, an example in which In composition ratio w of the well layer **42** ($In_wGa_{1-w}N$) is made to increase toward the first direction D**1**, is shown. In this example, In composition ratio w of the n-th well layer **42**(*n*) is increased from 0.08 to 0.12 toward the first direction D**1**.

In FIG. **6**B, an example in which In composition ratio b of the barrier layer **41** ($In_bGa_{1-b}N$) is made to decrease toward the first direction D**1** and In composition ratio w of the well layer **42** ($In_wGa_{1-w}N$) is made to increase toward the first direction D**1**, is shown. In this example, In composition ratio b of the n-th barrier layer **42**(*n*) is decreased from 0.07 to 0.03 toward the first direction D**1** and In composition ratio w of the n-th well layer **42**(*n*) is increased from 0.14 to 0.16 toward the first direction D**1**.

As shown in FIGS. **6**A and **6**B, In composition ratio b of the barrier layer **41** and In composition ratio w of the well layer **42** decrease or increase while accompanied with the minute increase and decrease. In the embodiment, decrease or increase including such minute increase and decrease is also included in the decrease of In composition ratio b of the barrier layer **41** and the increase of In composition ratio w of the well layer **42**.

FIGS. **7**A and **7**B, and **8**A and **8**B show change of energy bands by the change of In composition ratios of the well layers, respectively.

In FIG. **7**A, the profile of In composition ratios of a case in which wn=0.11, wp=0.15, i.e., Δw=0.04, and bp=0.00, bn=0.04, i.e., Δb=0.04 (where wn and wb are In composition ratios of the well layer **42**, and by and bn are In composition ratios of the barrier layer **41**), is represented. In addition, the thickness t_w of the well layer **42** is 3 nm, and the thickness t_b of the barrier layer **41** is 5 nm.

In FIG. **7**B, the energy band diagram of a valence band at the In composition ratio profile represented in FIG. **7**A is represented. In FIG. **7**B, the energy band diagram when current amount flowing to the light emitting layer **40** is changed, is represented. Current amount J1 is 74 A/cm^2, current amount J2 is 184 A/cm^2, and current amount **33** is 280 A/cm^2.

As represented in FIGS. **7**A and **7**B, change of the energy band diagram by change of the current amounts J1 to J3 is small. In contrast, when the absolute value Δw difference of In composition ratios is 0.04, the energy band diagram of the valence band will not be rectangular.

In FIG. **8**A, the profile of In composition ratios of a case in which wn=0.07, wp=0.19, i.e., Δw=0.12, and bp=0.00, bn=0.04, i.e., Δb=0.04 (where wn and wb are In composition ratios of the well layer **42**, and by and bn are In composition ratios of the barrier layer **41**), is represented. In addition, the thickness t_w of the well layer **42** is 3 nm, and the thickness t_b of the barrier layer **41** is 5 nm.

In FIG. **8**B, the energy band diagram of a valence band at the In composition ratio profile represented in FIG. **8**A is represented. In FIG. **8**B, the energy band diagram when current amount flowing to the light emitting layer **40** is changed, is represented. Current amount J4 is 82 A/cm^2, current amount J5 is 176 A/cm^2, and current amount J**6** is 268 A/cm^2.

As represented in FIGS. **8**A and **8**B, change of the energy band diagram by change of the current amounts **34** to **36** is small. In contrast, when the absolute value Δw of the difference of In composition ratios is 0.12, the energy band diagram of the valence band will not be rectangular.

For the semiconductor light emitting device **110** according to the embodiment shown in FIGS. **4**A to **4**D, the absolute value Δw of the difference in In composition ratio is 0.08. That is, the absolute value Δw of the difference in In composition ratio for the semiconductor light emitting device **110** locates between the absolute value Δw of the difference in In composition ratio shown in FIGS. **7**A and **7**B and the absolute value Δw of the difference in In composition ratio shown in FIGS. **8**A and **8**B.

In this case, as shown in FIG. **4**C, the energy band diagram of the valence band becomes rectangular.

From the above-mentioned results, it is understood that the absolute value Δw of the difference in In composition ratio of the well layer **42** is desirable to be greater than 0.04 and smaller than 0.12.

FIGS. **9**A to **9**D are schematic views illustrating the profile of increase and decrease in In composition ratio, respectively.

In the semiconductor light emitting device **110** according to the embodiment, In composition ratio of the barrier layer **41** decreases toward the first direction D**1**, and In composition ratio of the well layer **42** increases toward the first direction D**1**.

In FIGS. **9**A to **9**D, an example of the increase and decrease in In composition ratio is schematically shown, respectively.

The profile of the increase and decrease in In composition ratio shown in FIG. **9**A, is a case in which In composition ratio of the barrier layer **41** decreases in a curved line toward the first direction D**1**, and In composition ratio of the well layer **42** increases in a curved line toward the first direction D**1**.

The profile of the increase and decrease in In composition ratio shown in FIG. **9**B, is a case in which In composition ratio of the barrier layer **41** decreases in a stepwise fashion toward the first direction D**1**, and In composition ratio of the well layer **42** increases in a stepwise fashion toward the first direction D**1**.

The profile of the increase and decrease in In composition ratio shown in FIG. **9**C, is a case in which In composition ratio of the barrier layer **41** decreases toward the first direction D**1** while repeating the minute increase and decrease, and In composition ratio of the well layer **42** increases toward the first direction D**1** while repeating the minute increase and decrease.

The profile of the increase and decrease in In composition ratio shown in FIG. **9**D, is an example in which change in In composition ratio becomes slow at the boundary position between the barrier layer **41** and the well layer **42**.

In any of the above-mentioned cases shown in FIGS. **9**A to **9**D, it is included that In composition ratio of the barrier layer **41** decreases toward the first direction D**1**, and In composition ratio of the well layer **42** increases toward the first direction D**1**.

The profile of increase and decrease in In composition ratio may also be one other than the above-mentioned profiles. Also, a profile constituted by suitably combining the profiles of FIGS. **9**A to **9**D may be used.

FIGS. **10**A to **10**H are schematic views showing an example of inclination of In composition ratios of the barrier layer and the well layer, respectively.

In each of FIGS. **10**A to **10**H, the vertical axis represents In concentration ratio and the horizontal axis represents a position. In these drawings, for the sake of clear explanation, one profile for In composition ratio is shown for each of the barrier layer **41** and the well layer **42**.

In the example of inclination of In composition ratio shown in FIG. **10**A, In composition ratios of the barrier layer **41** and the well layer **42** increase toward the first direction D**1**. The profile of In composition ratio shown in FIG. **10**A is defined as P(a).

In the example of inclination of In composition ratio shown in FIG. **10**B, In composition ratio of the barrier layer **41** is constant, and In composition ratio of the well layer **42** decreases toward the first direction D**1**. The profile of In composition ratio shown in FIG. **10**B is defined as P(b).

In the example of inclination of In composition ratio shown in FIG. **10**C, In composition ratio of the barrier layer **41** increases toward the first direction D**1**, and In composition ratio of the well layer **42** is constant. The profile of In composition ratio shown in FIG. **10**C is defined as P(c).

In the example of inclination of In composition ratio shown in FIG. **10**D, In composition ratio of the barrier layer **41** decreases toward the first direction D**1**, and In composition ratio of the well layer **42** is constant. The profile of In composition ratio shown in FIG. **10**D is defined as P(d).

In the example of inclination of In composition ratio shown in FIG. **10**E, In composition ratio of the barrier layer **41** increases toward the first direction D**1**, and In composition ratio of the well layer **42** increases toward the first direction D**1**. The profile of In composition ratio shown in FIG. **10**E is defined as P(e).

In the example of inclination of In composition ratio shown in FIG. **10**F, In composition ratio of the barrier layer **41** decreases toward the first direction D**1**, and In composition ratio of the well layer **42** increases toward the first direction D**1**. The profile of In composition ratio shown in FIG. **10**F is defined as P(f).

Profile P (f) is a profile of In composition ratio of the semiconductor light emitting device **110** according to the embodiment.

In the example of inclination of In composition ratio shown in FIG. **10**G, In composition ratio of the barrier layer **41** increases toward the first direction D**1**, and In composition ratio of the well layer **42** decreases toward the first direction D**1**. The profile of In composition ratio shown in FIG. **10**G is defined as P(g).

In the example of inclination of In composition ratio shown in FIG. **10**H, In composition ratio of the barrier layer **41** decreases toward the first direction D**1**, and In composition ratio of the well layer **42** decreases toward the first direction D**1**. The profile of In composition ratio shown in FIG. **10**H is defined as P(h).

FIG. **11** illustrates internal quantum efficiencies.

In FIG. **11**, simulation calculation results of internal quantum efficiencies IQE corresponding to In composition ratio profiles P(a) to P(h) shown in FIGS. **10**A to **10**H, are shown.

In the calculation of internal quantum efficiency, the thickness tw of the barrier layer **41** is set to 5 nm and the thickness tb of the well layer **42** is set to 2.9 nm. Furthermore, In composition ratio of the barrier layer **41** is from 0.00 to 0.04 (the absolute value of the difference $\Delta w=0.04$) when In composition ratio of the barrier layer **41** is inclined, and it is assumed that In composition ratio of the well layer **42** is from 0.08 to 0.16 (the absolute value of the difference $\Delta w=0.08$) when In composition ratio of the well layer **42** is inclined.

For all cases, 8 barrier layers **41** and 8 well layers **42** are stacked, and all of the 8 barrier layers **41** and 8 well layers **42** are defined to have In composition ratio profiles shown in FIGS. **10**A to **10**H.

As shown in FIG. **11**, profile P(f) of In composition ratio of the semiconductor light emitting device **110** according to the embodiment, leads to a highest internal quantum efficiency among the eight profiles P(a) to P(h).

Here, profile P(e) has also lead to the same internal quantum efficiency as the internal quantum efficiency of profile P (f).n However, like in the profile P(e) shown in FIG. **10**E, the in a configuration in which In composition ratio of the barrier layer **41** increases toward the first direction D**1**, In composition ratio of the barrier layer **41** on the side of the well layer **42** neighboring toward the first direction D**1** becomes high. For this reason, the crystallinity of the well layer **42** stacked on this barrier layer **41** tends to be degraded.

Therefore, profile P (f) of In composition ratio of the semiconductor light emitting device **110** according to the embodiment, which is a profile having a good internal quantum efficiency and good crystallinity, is the optimal one.

FIGS. **12**A and **12**B, and **13**A and **13**B illustrate relationships between In composition ratio of the barrier layer **41** and the internal quantum efficiency, respectively.

Any of the drawings shows simulation results when only the 8th barrier layer **41** of 8 barrier layers **41**, which is nearest to the p-type semiconductor layer **50**, is made to have inclined In composition ratio. Further, internal quantum efficiencies IQE are simulation results when current with current amount of current 170 A/cm^2 is flown into the light emitting layer **40**.

FIG. **12**A shows relationships between the absolute value Δb of the difference in In composition ratio of the barrier layer **41** and the internal quantum efficiency IQE. In FIG. **12**A, internal quantum efficiencies IQE when the thickness of the barrier layer **41** is 5 nm and 10 nm, are illustrated.

According to the simulation results shown in FIG. **12**A, it is understood that the absolute value Δb of the difference in In composition ratio of the barrier layer **41** has an optimal value. Moreover, it is also understood that the optimal value changes depending on the thickness of the barrier layer **41**.

FIG. **12**B shows relationships between the difference in In composition ratio per unit thickness (gradient of In composition ratio ($\Delta b/t_b$)) of the barrier layer **41** and the internal quantum efficiency IQE. In FIG. **12**B, internal quantum efficiencies when the thickness of the barrier layer **41** is 5 nm and 10 nm, are illustrated. The gradient of In composition ratio in In composition ratio of the barrier layer **41** is referred to as a value of the absolute value Δb of the difference in In composition ratio divided by the thickness t_b.

According to the simulation results shown in FIG. **12**B, it is understood that the gradient of In composition ratio ($\Delta b/t_b$) of the barrier layer **41** has an optimal value irrespective of the thickness of the barrier layer **41**.

FIG. **13**A shows relationships between the gradient of In composition ratio ($\Delta b/t_b$) of the barrier layer **41** and the rate of rise of the internal quantum efficiency IQE_AV. In FIG. **13**A, the rates of rise of the internal quantum efficiency IQE_AV when the thickness of the barrier layer **41** is 5 nm and 10 nm, are illustrated.

According to the simulation results shown in FIG. **13**A, it is understood that the rate of rise of the internal quantum efficiency IQE_AV becomes higher as the thickness of the barrier layer **41** increases.

FIG. **13**B shows relationships between the ratio R (($\Delta b/t_b$)/($\Delta w/t_w$)) between the gradient of In composition ratio of the barrier layer **41** ($\Delta b/t_b$) and the difference per unit thickness in In composition ratio of the well layer **42** (the gradient of In composition ratio ($\Delta w/t_w$)) and the rate of rise of the internal quantum efficiency IQE_AV. In FIG. **13**B, the rates of rise of the internal quantum efficiency IQE_AV when the thickness of the barrier layer **41** is 5 nm and 10 nm, are illustrated.

According to the simulation results shown in FIG. **13**B, it is understood that the rate R has an optimal value. Moreover, it is also understood that the rate of rise of the internal quantum efficiency IQE_AV becomes higher as the thickness of the barrier layer **41** increases.

From the simulation results shown in FIG. **13**B, it is preferable to make the ratio R, for example, not less than 0.1 and not more than 0.4, more preferably not less than 0.2 and not more than 0.3.

Although, the embodiment and the example described above, has described In composition in the III group elements of the barrier layer **41** and the well layer **42**, they are also applicable to compositions of other than In.

Further, although the embodiment and the example has described a case in which a light emitting layer **40** has MQW structure, the In composition ratio profiles of the barrier layer **41** and the well layer **42** described above are also applicable to a light emitting layer **40** having SQW (Single Quantum Well) structure.

According to the embodiment, a semiconductor light emitting device having a high light emission efficiency is provided.

In the specification, "nitride semiconductor" shall include semiconductors with all composition ratios in chemical formula represented by of $B_\alpha In_\beta Al_\gamma Ga_{1-\alpha-\beta-\gamma}$ ($0\leq\alpha\leq1$, $0\leq\beta\leq1$, $0\leq\gamma\leq1$, and $\alpha+\beta+\gamma=1$), where composition ratios α, β and γ are changed within each range. Furthermore, semiconductors with the chemical formula further including V group elements other than N (nitrogen) and any of various dopants added for controlling conduction type etc. shall also be included in the "nitride semiconductor".

As above, the embodiment of the invention has been described with reference to the specific examples. However, the invention is not limited to these specific examples.

For example, even if specific configurations of elements of the semiconductor light emitting device, such as, an n-type semiconductor, a p-type semiconductor, an active layer, a well layer, a barrier layer, an electrode, a substrate, and a buffer layer are variously modified by a person skilled in the art, the modified configurations shall also included in the scope of the invention, as long as the person skilled in the art can implement the invention similarly to achieve the similar effect by suitable selection from a known scope.

Further, combination of two or more elements of each of the specific examples within a technically possible scope, shall also be included in the invention.

While certain embodiments have been described, these embodiments have been presented by way of example only, and are not intended to limit the scope of the inventions. Indeed, the novel embodiments described herein may be embodied in a variety of other forms; furthermore, various omissions, substitutions and changes in the form of the embodiments described herein may be made without departing from the spirit of the inventions. The accompanying claims and their equivalents are intended to cover such forms or modifications as would fall within the scope and spirit of the invention.

What is claimed is:

1. A semiconductor light emitting device, comprising:

an n-type semiconductor layer containing a nitride semiconductor;

a p-type semiconductor layer containing a nitride semiconductor; and

a light emitting layer provided between the n-type semiconductor layer and the p-type semiconductor layer,

the light emitting layer including a barrier layer containing $In_bGa_{1-b}N$ ($b\geq0$), and a well layer stacked with the barrier layer in a direction going from the n-type semiconductor layer toward the p-type semiconductor layer, the well layer containing $In_wGa_{1-w}N$ ($w>b$),

the barrier layer has a first end and a second end, the first end is located on a side of the n-type semiconductor layer and has a first value of an In composition ratio, the second end is located on a side of the p-type semiconductor layer and has a second value of an In composition ratio,

the first value being larger than the second value,

an absolute value of a difference between the first value and the second value is greater than 0.02 and smaller than 0.06,

the well layer has a third end and a fourth end, the third end is located on a side of the n-type semiconductor layer and has a third value of an In composition ratio, the fourth end is located on a side of the p-type semiconductor layer and has a fourth value of an In composition ratio,

the third value being smaller than the fourth value,

an absolute value of a difference between the third value and the fourth value is greater than 0.04 and smaller than 0.12,

a thickness of the barrier layer is not more than 10 nanometers, and

a thickness of the well layer is not less than 2.5 nanometers and not more than 6 nanometers.

2. The device according to claim **1**, wherein a ratio of a first change rate to a second change rate is not less than 0.2 and not more than 0.3, the first change rate is a change in an In composition ratio in the barrier layer with respect to a unit thickness of the barrier layer, and the second change rate is a change in an In composition ratio in the well layer with respect to a unit thickness of the well layer.

3. The device according to claim **1**, wherein the second value is 0.00.

4. The device according to claim **1**, wherein the absolute value is greater than 0.02 and smaller than 0.04.

5. The device according to claim **4**, wherein the second value is 0.00.

6. The device according to claim **1**, wherein the absolute value is not less than 0.06.

7. The device according to claim **1**, wherein the third value is not more than 0.10.

8. The device according to claim **1**, wherein

the barrier layer is provided in a plurality,

the well layer is provided in a plurality, and

the plurality of barrier layers and the plurality of well layers are stacked alternatively.

9. The device according to claim **8**, wherein

in all of the plurality of barrier layers, an In composition ratio in the III group elements decreases in the direction, and

in all of the plurality of well layers, an In composition ratio in the III group elements increases in the direction.

10. The device according to claim **8**, wherein

in a part of the plurality of barrier layers, an In composition ratio in the III group elements decreases in the direction, and

in a part of the plurality of well layers, an In composition ratio in the III group elements increases in the direction.

11. The device according to claim **1**, wherein an In composition ratio of the barrier layer and an In composition ratio of the well layer change linearly.

12. The device according to claim **1**, wherein an In composition ratio of the barrier layer and an In composition ratio of the well layer change in a stepwise fashion.

13. The device according to claim **1**, wherein an In composition ratio of the barrier layer and an In composition ratio of the well layer change in a curved line.

14. The device according to claim **1**, wherein an In composition ratio of the barrier layer and an In composition ratio of the well layer change while repeating a minute increase and decrease in the respective In composition therein.

15. The device according to claim **1**, wherein an In composition ratio of the barrier layer is not more than the first value and not less than the second value.

16. The device according to claim **15**, wherein the second value is 0 or more.

17. The device according to claim **1**, wherein an In composition ratio of the well layer is not less than the third value and not more than the forth value.

18. The device according to claim **17**, wherein the third value is more than the first value.

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